CAD-Aided Preoperative Simulation in Pediatric Orthopedics: The Case Study of Ollier's Disease

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Abstract

This work shows a preoperative simulation procedure with Computer Aided Design (CAD) 3D software for a patient suffering from Ollier's disease. This pathology is very rare and occurs in extremely different ways depending on the case. Consequently, it is difficult to establish a correct surgical strategy that can be applied in a similar way to all patients. Computer Aided Surgical Simulation (CASS) process uses advanced modeling technologies to reproduce bony anatomy and simulate the surgery. The starting point is represented by the 3D digital model of the bone obtained from tomographic images. Through CAD modeling software such as Creo Parametric and following surgeons directives, engineers can provide doctors with orthopedic simulation and expectation of achievable surgical outcome. If virtual surgical prediction doesn't meet doctors requirements, model is regenerated and it is possible to seek for a better solution. CASS process allow for extensive surgical planning, enhancing accuracy in theatre and enriching the amount of medical information that is needed to perform complex orthopedic procedures. In conclusion, the possibility to recognize in advance the overall orthopedic situation and outcoming expectancy represent an extraordinary upgrade of current surgical state of the art, leading to minimally invasive surgeries and patient-specific solutions.

Keywords
3D modeling, CASS, CAD, preoperative planning, parametric software.

1. Introduction
Ollier's disease is a pathology characterized by the presence of intraosseous cartilage tumors called endocromes which can be extremely variable depending on the size, number, location, evolution, age of onset and diagnosis. For this reason, each case must be considered in its uniqueness and requires a particular and specific treatment. (Silve and Jüppner 2006, Kumar et al. 2015). This article considers a patient with femoral deformity caused by Ollier's disease. The research conducted by Angelini et al. (2020) led to a systemic literature review of articles dealing with patients with limb deformities caused by Ollier's disease. These patients were surgically treated with variable techniques, including osteotomies and external fixation, intramedullary nails, epiphysiodesis, and nail lengthening.

In the case in question, the surgeons decided to proceed with a non-invasive treatment for the correction of the deformity of the femur. It was therefore decided to proceed with the insertion of an intramedullary nail designed to lengthen the femur with precision and control.
In recent decades, the development of advanced information technologies has led to the growth of several sectors. In

particular, the use of preoperative simulations is increasingly spreading in orthopedic surgery. These methodologies make surgical procedures less invasive, more effective and safer. Their utility is manifest in cases of patients suffering from particularly serious and varied diseases, as in the case study. This article therefore aims to illustrate the previous surgical simulation for a patient with Ollier's disease that takes place through parametric modeling CAD software. The entire work was made possible by a fundamental collaboration between the Department of Industrial Engineering (DIN) of the University of Bologna and the Rizzoli Orthopedic Institute (IOR) of Bologna. The purpose of this collaboration is represented by the design of engineering tools that are used in the medical field.

1.1 Objectives

This paragraph lists all the objectives pursued by this research.

- Establish the deformation magnitude and the suitable degree of correction using the Creo Parametric CAD software
- Provide an appropriately sized CAD representation of the tools needed for the operation.
- Provide a virtual model that clarifies the surgical routine and the achievable outcomes. This model must be modifiable according to the doctors needs and advices.
- Reduce the overall operative time and patient surgical exposure consequently.
- Provide patients with a better understanding of their clinical picture and needed surgical treatment.

2. Literature Review

The growing presence of articles that address the use of computer-assisted simulation in surgical orthopedic procedures demonstrates the interest aroused by this innovative methodology. The work of Mediouni and Volosnikov (2015) shows that in order to have an effective methodology it is necessary to consider several factors such as feedback, skills acquisition, simulation fidelity and timing. In fact, the correct preoperative simulation must be obtained in a short time. In this way, there are no excessive cost increases that can make the procedure inefficient (Bae, 2015).

The first surgical reports on the use of 3D technologies come from dentistry and the maxillofacial field. An example is provided by the works of Gaetano et al. (2007), Aboul-Hosn Centenero et al. (2012) and Hsu et al. (2013) where 3D digital models were obtained from tomographic images through the use of guide models, digital displays and laser scanners.

Interesting results have been obtained in maxillo-mandibular osteotomy interventions through the use of advanced tools. An example is given by the work of Li et al. (2013) in which the parametric software Uni graphics NX 7.5 was used to obtain orthognathic templates. In the article by Cervidanes et al. (2010), on the other hand, a surgical simulation procedure applied in the cranio-maxillofacial area and obtained through the PROPLAN CMF ™ software is described. In orthopedics, however, many doubts have emerged about the efficiency and convenience of using the CAD methodology (Dutta 2006). The high cost of the procedure and the increase in diagnosis times make, in fact, this innovative procedure unsuitable for simple surgical interventions. Therefore, the traditional procedure with formulation of the surgical plan based exclusively on two-dimensional images is currently the most used surgical technique. However, in cases of rare and particularly complex articular bone fractures, computer simulation in the preoperative planning phase is necessary in order to obtain excellent results in theatre.

The main CAD simulation methods used in the orthopedic field and present in the literature are listed below. The most widely used software for simulation in the orthopedic field is Materialize Mimics. This is image processing software for 3D design and modeling, commercially available and developed by Materialize NV. Examples of the use of Mimics are given by the plans made by Wong et al. (2010) and Jiang et al. (2019). The software allows for patient-specific surgical guides to be designed as well as emerges from the studies by Zhang et al. (2019) and Shi et al. (2019).

An alternative is represented by the work of Sariali et al. (2012) using Hip-PlanTM software (Sym bios, Yverdon, Switzerland) for hip arthroplasty planning. The article by Wong et al. (2020) shows the design of a patient-specific titanium implant made using parametric CAD software. Interesting studies were carried out aimed at obtaining the exact reconstruction of the bones and the right placement of the screws to be implanted in the bone following the operation (Milojevic et al., 2010). Furthermore, preoperative simulation procedures and design of custom-made surgical guides tested on cadavers have been developed (Helguero et al. 2015, Wong et al. 2012). An interesting work by Perica et al. (2017) evaluates the possibility of carrying out simulations also considering the presence of soft tissues.

To conclude, we consider the works that emerged from our study. In the works "Computer-Aided Surgical Simulation for Correcting Complex Limb Deformities in Children" (Frizziero et al. 2020) and "Effectiveness Assessment of CAD Simulation in Complex Orthopedic Surgery Practices" (Frizziero et al. 2021) the simulation procedure is analyzed at CAD using mainly free open-source software. In the works "An Innovative and Cost-Advantage CAD Solution for Cubitus Varus Surgical Planning in Children" (Frizziero et al. 2021) and "In-House, Fast FDM Prototyping of a Custom Cutting Guide for a Lower-Risk Pediatric Femoral Osteotomy" (Frizziero et al. 2021) the same methodology is used for the production of custom-made surgical guides.

3. Methods

The simulation of the intervention starts from the three-dimensional reconstruction of the anatomical part (Figure 1). The methodology used to obtain this model has been extensively described in the works reported in the literature of which this application is the continuous (Osti et al. 2019, Frizziero et al. 2019, Caligiana et al. 2020, Frizziero et al. 2020, Napolitano et al. 2020). The particular case examined required a direct confrontation with medical specialists to develop an effective and precise approach. In this way, the engineer can independently make the agreed choices. As a first step, the extent of the deformation in all directions was measured. This procedure was made possible by the creation of appropriate basic geometries (planes, axes and points) on the three-dimensional model of the bone, initially devoid of references (Figure 2). For a correct definition of the measures and in order to verify the exact range of values for the characteristic angles, it was necessary to consider the anatomy of the patient's healthy femur (Figure 3).

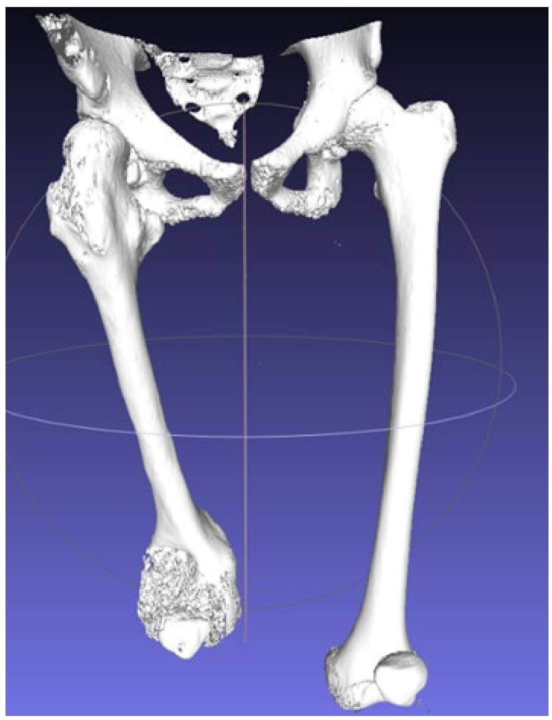


Figure 1. Reconstructed three-dimensional model of the anatomical part.

The operation involves an osteotomy in the area just above the epiphysis (Figure 4) to allow the correct regeneration of the bone tissue. The osteotomy takes place along a cutting plane that is approximately perpendicular to the frontal plane of the bone. A through hole is then made, suitably inclined, in the femoral segment obtained from the cut: the entry point must necessarily be the intercondylar fossa, while the direction is chosen specifically to correct the deformation in two dimensions (Figure 5).

Figure 2. Generation of elementary geometries.

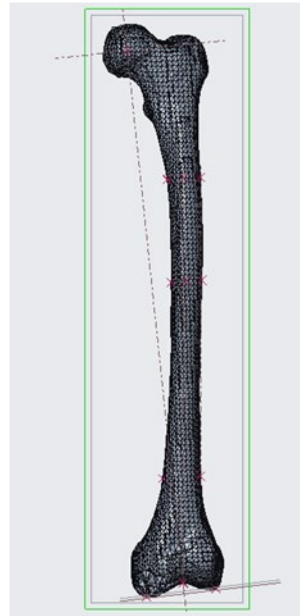


Figure 3. Healthy femur.

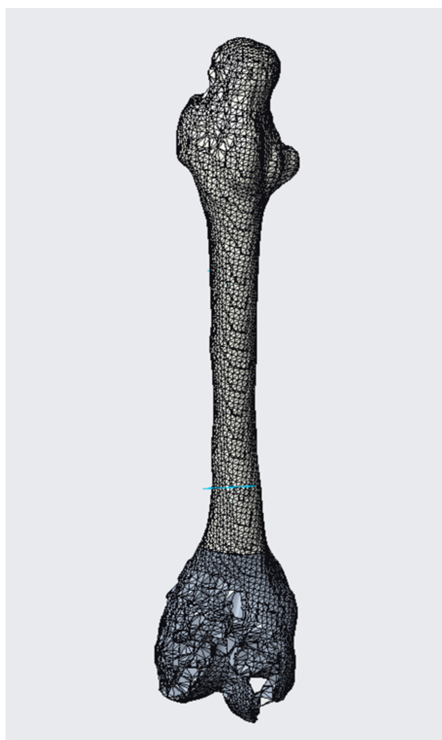


Figure 4. Cutting plan for osteotomy

It is necessary to leave a minimum thickness of at least 3 mm around the entire section of the hole to allow a correct sealing of the tissue (Figure 6.a). The upper section of the bone made by the initial osteotomy must also be perforated (Figure 6.b). In this way, the required depth is guaranteed for the entry of an intramedullary nail that has a fixed length chosen in the catalog.

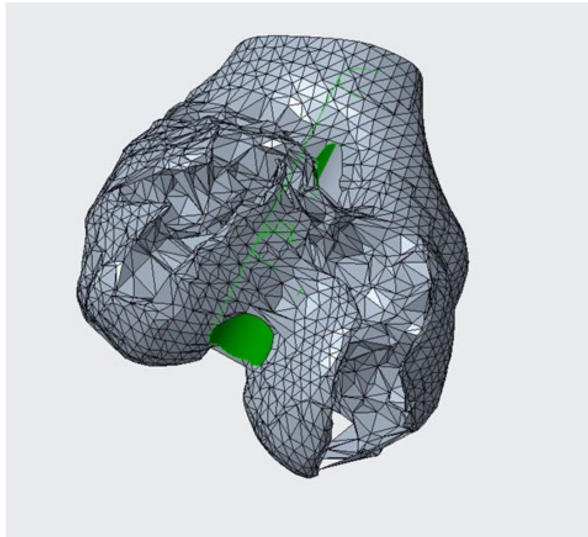


Figure 5. Hole for the intramedullary nail in the lower section

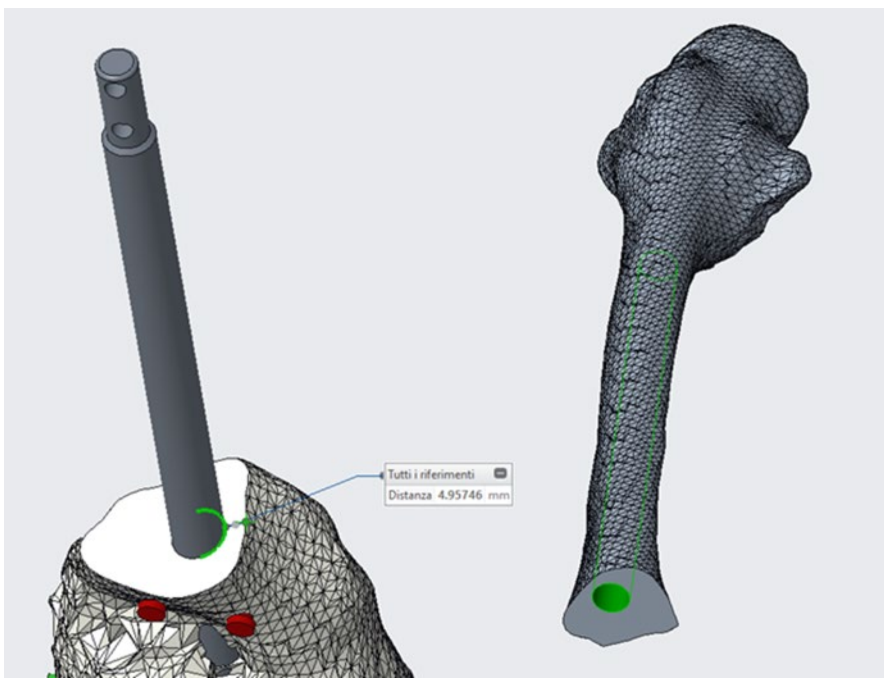


Figure 6. Minimum thick for bone tissue (a) and hole in the diaphysis (b)

The insertion of the intramedullary nail is guided by two screws located near the cutting area (Figure 7) and will allow the two parts to be correctly aligned, solving the deformation as much as possible. Fixing the organ is complex given the high porosity of the distal epiphysis caused by the pathology. It is therefore very useful to have the possibility of analyzing in advance, through the three-dimensional model, the most suitable areas for tightening the screws. After having created the various parts for the simulation, we proceed with the assembly in the dedicated area of CREO: the constraints between the axes and the notable points of the models are set and then the final result is evaluated. The upper part of the femur is rigidly fixed in the working space (Figure 8); then the intramedullary nail is inserted paying attention to the correct direction. The positions of the upper fixing screws are obtained (Figure 9).

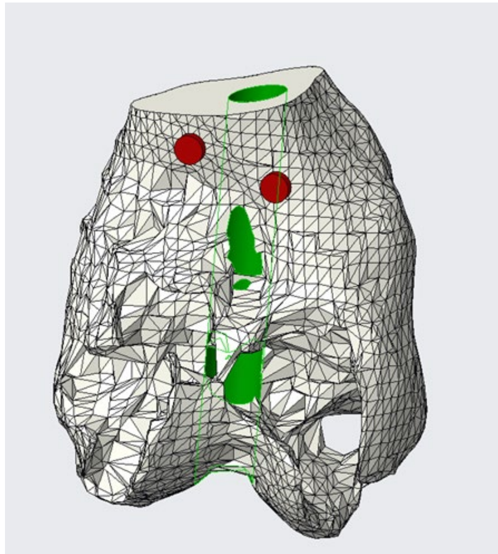


Figure 7. Guide screws (red)

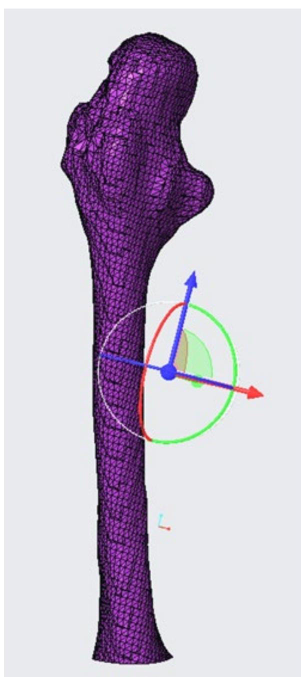


Figure 8. Placement of the starting component. Figure 9. Insertion of the nail in the upper section.

As a final step, the section with the distal epiphysis is also positioned following the axis of the dimensioned hole (Figure 10). By inserting the screws in the appropriate holes on the intramedullary nail, it is possible to check the exact fixing positions on the bone tissue and avoid placement in the most porous and therefore less resistant areas (Figure 11).

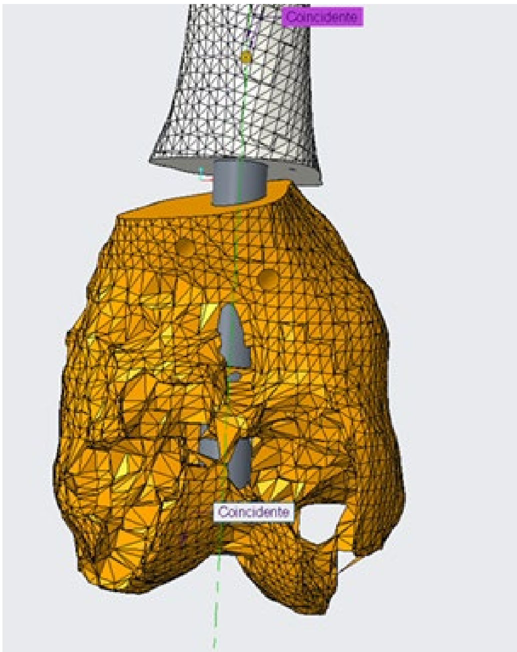


Figure 10. Lower section positioning.

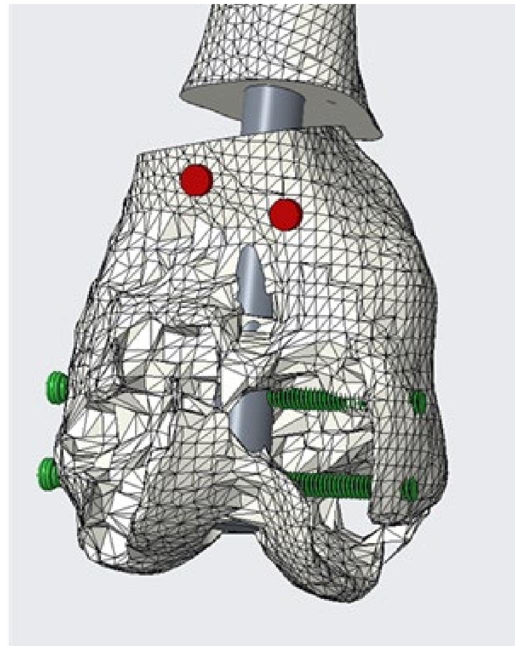


Figure 11. Fixing screws (green).

4. Data collection

The necessary measures for the definition of all the operations in the intervention were taken through the CREO "measure" application. Being a parametric software dedicated to mechanical modeling, it has a high precision and allows great flexibility during data collection (Figure 12). Specifically, the characteristic angles of the examined anatomy were found based on tables provided by orthopedic surgeons (Table 1).

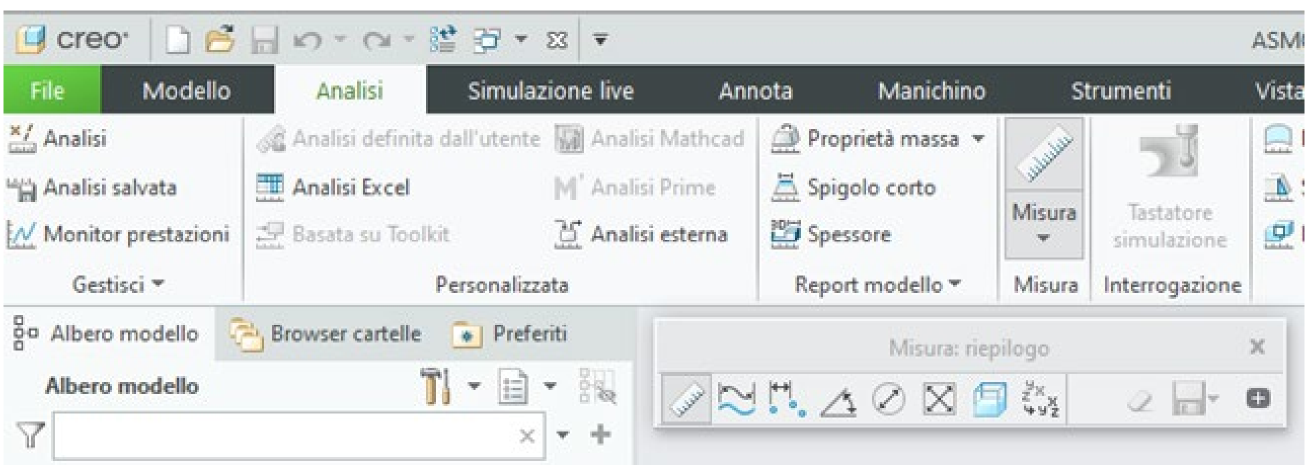
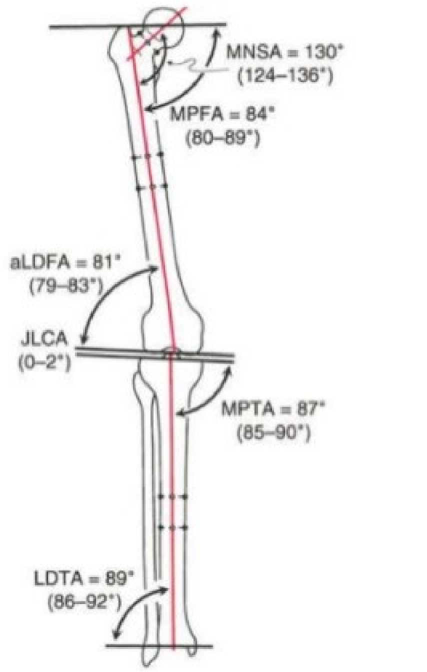
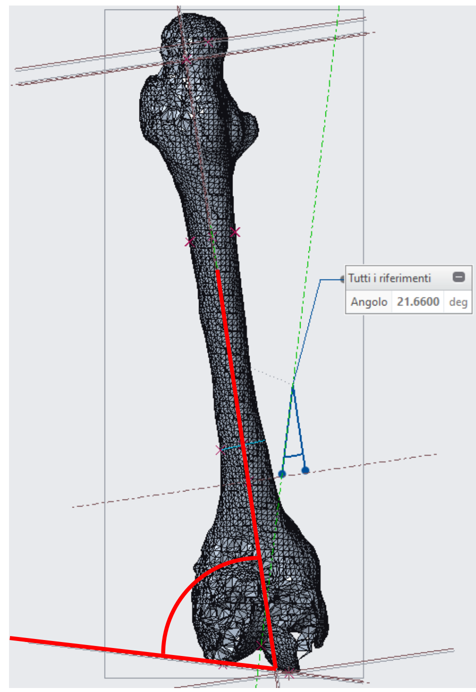
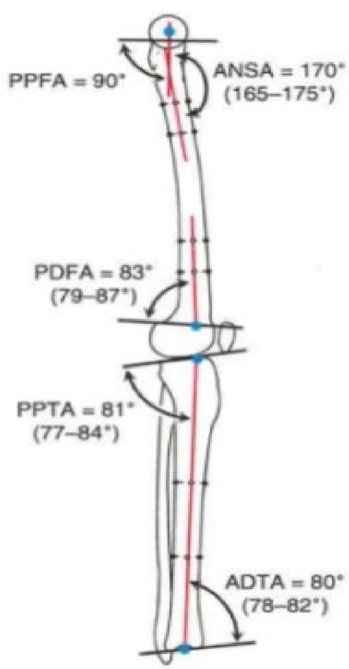


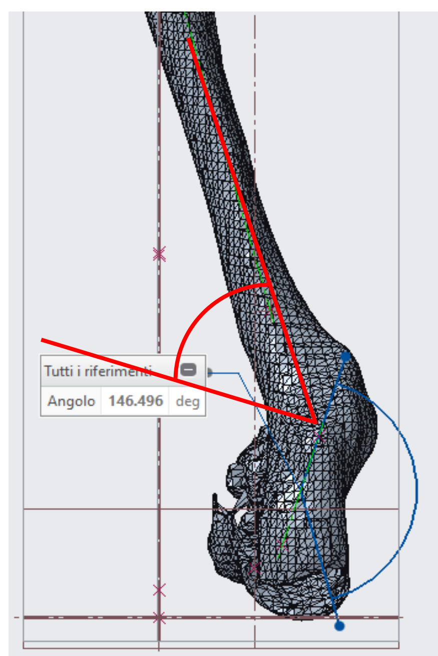
Figure 12. Analysis section.

Table 1. Pre-operation characteristic angles.

<table>
<tr><th>VIEW</th><th>CHARACTERISTIC MEASURES</th><th>MEASURES DETECTED</th></tr>
<tr><td>FRONT</td><td>

The frontal deformation affects the LDTA angle which should normally assume values between 86 ° and 92 °.</td><td>

LDTA = 90°- 21.6° = 68.4°
It is necessary to increase this angle by making the pin insertion hole with an adequate inclination.</td></tr>
<tr><td>LATERAL</td><td>

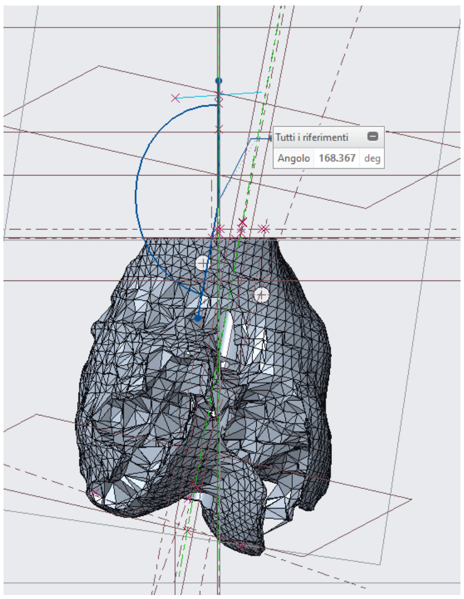
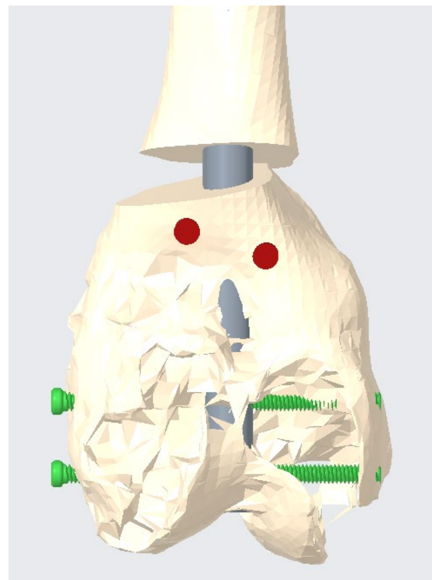
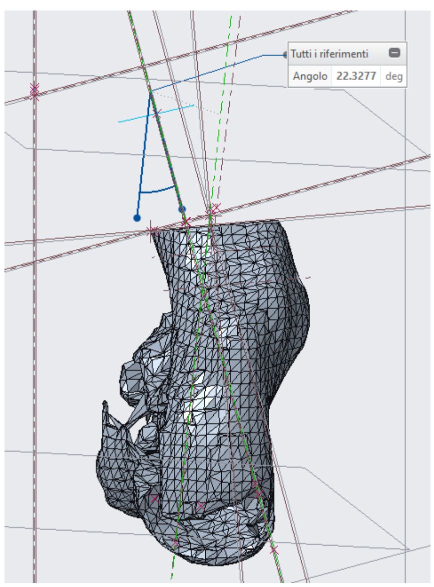
The lateral deformation concerns an ADTA angle, as in the figure, which is normally between 78 ° and 80 °.</td><td>

ADTA = 90°- (180° - 146.5°) = 56.6°
Therefore it should be increased this angle to as close as possible to the characteristic value.</td></tr>
</table>

5. Results and Discussion

The distortion was resolved by an inclination in two directions of the hole for the intramedullary nail in the epiphysis segment. It was necessary to maintain minimum thicknesses and consider the constraints given by the patient's anatomy. For this reason, the increase in the two angles of interest was limited but significantly better values were still achieved. The results are summarized in Table 2.

Table 2. Post-operation characteristic angles.

VIEW	CORRECTION	POST-OPERATION
FRONT	 After tilting the pin hole by 180 °-168.4 ° = 11.6 ° The LDTA angle was increased, obtaining a final value of 80 °.	
LATERAL	 With an inclination of 22.3 °, a final value of the ADTA angle of 78.8 ° is obtained.	

Following doctors guidelines, it was possible to choose from the catalog the suitable surgical tools: each screw and pin were appropriately sized on CREO and used in the simulation to provide a final model that best reflects the real examined situation and its solution (Figure 13).

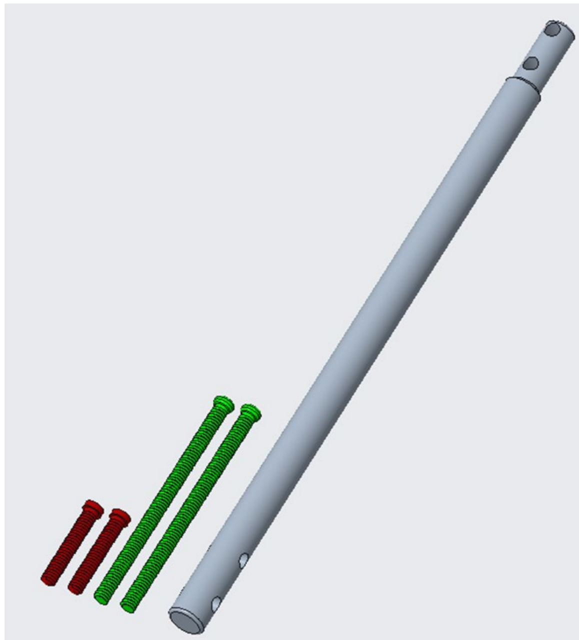


Figure 13. CAD model of surgical tools.

6. Conclusion

The simulation gave doctors an overview of the possible surgical outcome, complete with all the details and specific for the case under exam. The three-dimensional model, precisely dimensioned, allows an accurate analysis in pre-operative planning phase with a consequent reduction of risks and unforeseen in surgery and therefore possible delays. Especially in diseases that affect multiple directions and that vary completely depending on the bone considered and the patient, it is glaring the usefulness of such an accurate simulation method. Being able to rely on a reproduction of the anatomy once operated also enhance the surgeon-patient communication.

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Biography

Francesca Napolitano, Curzio Pagliari and **Paola Papaleo** completed their bachelor's degree in Mechanical Engineering at Alma Mater Studiorum University of Bologna. They are currently master's students in Mechanical Engineering.